

*Crisis Stability Indices  
for Adaptive Two-Layer Defenses*

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# CRISIS STABILITY INDICES FOR ADAPTIVE TWO-LAYER DEFENSES

by

Gregory H. Canavan

## ABSTRACT

This note derives a simple, approximate model that contains most of the features needed to understand the variation of crisis stability indices with defenses. Boost-phase defenses are subtractive; midcourse defenses are preferential and adaptive. Defenses protect some retaliatory missiles, but not enough to retaliate strongly. Missile restrikes penetrate poorly, so most of the first and second strikes are carried by aircraft, which makes discussion of factors that might reduce their pre-launch survivability important.

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## I. INTRODUCTION

This note extends earlier treatments of the crisis stability properties of two-layer defenses in which the first layer acts subtractively and the second preferentially.<sup>1</sup> Here, the second layer is taken to act adaptively as well. This paper illustrates the interaction of the two layers for an idealized case in which both sides have identical offensive and defensive forces, although their allocation strategies can be quite different.

Some idealization is useful because crisis stability models include a large number of complicated interactions<sup>2</sup> that can obscure the source of important results.<sup>3</sup> Moreover, earlier

calculations have indicated that the principal stability results are not overly sensitive to modest asymmetries in offensive and defensive forces. This note gives a simple, approximate discussion that is thought to contain most of the features needed to understand the behavior of stability indices and their optimization.

## II. BOOST-PHASE DEFENSES

The main elements of crisis stability models are inter-continental and submarine-launched ballistic missiles (ICBMs and SLBMs) plus bombers, cruise missiles, and carriers--or aircraft for short. The number of reentry vehicles (RVs) that penetrate given boost-phase space-based interceptor (SBI) defenses can be evaluated exactly,<sup>4</sup> but the results are awkward to manipulate. A simple analytic function approximating the number of ICBM reentry vehicles (RVs) that penetrate a constellation of K SBIs is<sup>5</sup>

$$R \approx mM \cdot e^{-fK/M}, \quad (1)$$

where  $m \approx 10$  is the number of RVs per missile,  $M \approx 270$  is the total number of heavy missiles on each side,  $f$  is the fraction of the SBIs within range of launch, and  $K$  is the number of SBIs in the constellation. For SBIs with divert velocities of  $V = 6$  km/s,  $f$  would be about 20% for heavy ICBMs in their current basing. It would drop to about 13% for fixed heavy missiles and 10% for mobile heavy missiles, if under START all were relocated into current heavy missile launch areas.<sup>6</sup> The fraction of SBIs available scales as  $v^{3/2}$  to other SBI divert velocities.

The number of RVs killed is  $mM(1 - e^{-fK/M})$ . For small  $K$  that is  $mfK$ , i.e. the number of SBIs within range, for which the RVs killed per SBI is about  $mf \approx 10 \cdot 0.13 \approx 1.3$ . For large  $K$  the total number of RVs killed is about  $mM$ .

About half of the Soviet modern ICBMs are fixed and half mobile, but given the long burn times of heavy mobile missiles, it isn't necessary to distinguish between the two. The extension to do so is straightforward. Fast singlets such as SS-25s have  $f \approx 2-3\%$ . Optimal allocations essentially give them a free ride through the SBIs, although the  $\approx 350$  singlets contemplated under

START don't carry enough RVs to impact most of the stability calculations below significantly.<sup>7</sup> Fast, singlet missiles have been studied<sup>8</sup> but are not included. Equation (1) gives the fraction of RVs penetrating the boost phase exactly for both small and large  $K$ , but overestimates it 10-20% for intermediate  $K$ .<sup>9</sup> Thus, the calculations below uniformly underestimate the effectiveness of boost-phase defenses.

It is useful to write the number of penetrating ICBM RVs as  $mMp$ , where  $p = e^{-fK/M}$  is the approximate fraction that penetrates the boost phase. For 270 START-constrained heavy missiles, 2,000 SBIs give  $p \approx \exp(-0.13 \cdot 2,000/270) \approx 0.4$ ; 4,000 SBIs give  $p \approx 0.15$ . The general relationship of  $p$  to  $K$  is shown by the top curve of Fig. 1.

According to Eq. (1), increasing the number of missiles or replacing current missiles with faster ones would only rescale the number of SBIs required as  $K \approx (M/f) \ln(mM/R) \cdot \alpha 1/f$ . Thus, it is not necessary to vary  $K$  and  $f$  independently; boost-phase effectiveness scales. The results for other values of  $f$  can be obtained by rescaling the abscissas of the figures below. For fixed boost-phase effectiveness  $R/mM$ ,  $K \approx (M/f)$ , so that it is not necessary to vary  $M$  either.

The U.S. and the Soviet Union each have about 20 submarines with a total of  $N \approx 400$  SLBMs with an average of  $n \approx 6$  RVs each. The fraction of the SLBMs that penetrate the SBIs can be written as before as  $q \approx e^{-fK/(N/L)}$ , where the factor  $L$  is the number of separated points from which SLBMs are launched. Thus,

$$q \approx (e^{-fK/M})^{LM/N} = p^{LM/N}. \quad (2)$$

For  $L = 20$  uncorrelated launches,  $q \approx p^{20 \cdot 270/400} \approx p^{13.5}$ , so that  $q \ll p < 1$ , and SLBMs would contribute little to the RVs penetrating the boost phase defenses.

$L$  can, however, be reduced, and the number of missiles per site  $N/L$  increased, by clustering the SLBMs before launch.<sup>10</sup> For one port or bastion plus one clustering point in each ocean,  $L = 4$ , and  $LM/N \approx 4 \cdot 270/400 \approx 2.7$ , so that  $q = e^{-fLK/N} \approx p^{2.7}$ . For that clustering, if ICBMs were suppressed by a factor of  $p \approx 0.4$ , SLBMs would be suppressed by a factor of  $q \approx (0.4)^{2.7} \approx 0.084$ , a



factor of 5 more. If, however, all SLBMs in each ocean were launched together, that would give  $L = 2$ ,  $LM/H \approx 1.35$ , and for  $p = 0.4$ ,  $q \approx 0.3$ , which isn't much lower than the penetration probability for ICBMs. The  $q$  values for other  $K$ 's are shown by the lower curve on Fig. 1.

The extent to which SLBMs can be clustered before launch is a critical issue for their effectiveness and survivability, but not for the parametric stability calculations performed below. Thus, the maximum clustering,  $L = 2$ , is used without further variation below.

The total number of ICBM and SLBM RVs penetrating boost-phase defenses is their sum, or

$$R \approx mMp + nNq. \quad (3)$$

For START,  $nN \approx mM$ , so the total number of penetrating RVs is  $\approx mM(p + q) \approx 2mMp$ , or about twice the number of penetrating RVs from ICBMs alone. The variation of performance and indices with offense and defense parameters is studied elsewhere;<sup>11</sup> the purpose of this note is to point out a few important relationships that do not depend on specific force asymmetries. Accordingly, it is assumed below that the same offensive forces apply to both sides and that both sides deploy identical defenses.

### III. MIDCOURSE DEFENSES

Midcourse defenses can be either nonpreferential or preferential. The former would just give another attrition factor of  $\approx p$ ; the latter could be more effective. Midcourse interceptors have ranges long enough to cover the whole target set defended, and even near-term sensors could have the capabilities required for them to act preferentially.

#### A. Preferential Defense

If  $R$  penetrating RVs attacked  $M$  targets uniformly, there should be  $\approx R/M$  RVs per target. Thus,  $R/M$  interceptors could defend any given target, and  $I$  interceptors could defend  $I/(R/M)$  targets. If there were  $D$  decoys per RV, there would be a total

of  $(1+D)R$  threatening objects, so that  $I$  interceptors could defend

$S = I / [(1+D)R/M] = IM / (1+D)R \approx I e^{fK/M} / (1+D)^{2m}$  (4)  
 targets, up to  $M$ . Thus, the number of survivors, and through it the stability indices, depends on the defenses through the combination  $I e^{fK/M} / (1+D)$ , which also determines effectiveness.<sup>12</sup> While the number of decoys is very important in determining the actual interceptor inventories needed, for stability calculations it is possible to absorb  $(1+D)$  into  $I$ , i.e. to treat the midcourse interceptors as "ideal," which is done below.

### B. Adaptive Defenses

If the defenses could not adapt to variations in the attack, the attacker could vary the numbers of RVs on each target. That would reduce the number of survivors to  $S \approx I / (2R - M)$ , which would produce a  $\approx 2$ -fold penalty for  $R \approx M$  penetrating RVs.<sup>13</sup> If, however, the defense could sense variations in the attack caused by either the attacker or by the random operation of the boost phase and use his interceptors to defend the targets that were the most lightly attacked, that could turn variations to the advantage of the defense. Such adaptation should be within reach of the sensors under development, because they would only have to get a rough count of the RVs attacking each target and transmit that small amount of information to the SBIs defending them.

The performance of an adaptive system can be seen most easily for  $I \approx 0$ . There, even with  $R/M > 1$  attacking ICBM RV per target ICBM there is a probability

$$\epsilon(I \approx 0) \approx (1 - p)^{mM/M} \approx (1 - e^{-fK/M})^m \quad (5)$$

that a target will receive no ICBM RVs at all and hence survive even without midcourse interceptors. For START offensive force levels such survival probabilities are not small. For  $p = 0.2$ , that probability is  $\approx 0.8^{10} \approx 0.11$ . About  $0.11 \cdot 270 \approx 29$  missiles would survive even without midcourse defenses.

For greater numbers of RVs the number surviving falls to low levels and defenses must be used. The probabilities of various numbers of arriving weapons must be summed and compared with the

number of interceptors available.<sup>14</sup> That determines the expected number of surviving targets, which for large attacks is<sup>15</sup>

$$\epsilon \approx (I/pR)^{0.9} \cdot p^{0.64}. \quad (6)$$

For  $p \approx 1$ , i.e. little boost-phase attrition,  $\epsilon \approx I/R$  as before.

For  $p = 0.15$ ,  $\epsilon \approx (I/R)^{0.3}$ , which is much larger for small  $I$ .

Adaptive defenses provide greater capability when the defenses are small, which is when they would be needed during deployment. Defending only the lightly attacked targets greatly increases  $\epsilon$ , particularly for strong boost-phase attrition.

### C. Attack and Defense Allocation

The RVs penetrating the boost-phase defenses can be used on ICBMs, aircraft, or value targets, i.e. military projection forces. It has, however, been shown that a targeting strategy that allocates about a third of the penetrating RVs to each of the three sets of targets induces defenses that allocate their interceptors similarly, and that joint allocation is not overly sensitive to changes by either side.<sup>16,17</sup>

Thus, for the basic calculations below it is assumed that a fraction  $x' = 0.3$  of the attack is allocated to strikes on missiles, a fraction  $y' = 0.3$  is allocated to strikes on air bases, and the remaining fraction  $1 - x' - y'$  is allocated to value targets. The primes denote the attacker's parameters; the defender's parameters are unprimed. The basic calculations also assume that a fraction  $g = x = 0.3$  of the defense is allocated to the defense of missiles, a fraction  $h = y = 0.3$  to air bases, and  $1 - g - h$  to value targets, except where noted.

The  $gI$  interceptors are allocated adaptively to the missiles that are attacked, and the  $hI$  interceptors are allocated adaptively to air bases that are attacked. The remaining  $(1 - g - h)I$  interceptors defend value targets subtractively. It is shown elsewhere<sup>18</sup> that this allocation of the attack is close to optimal for a range of defenses, and that using the same allocation for the defense and offense is also near optimal.

#### IV. FIRST STRIKES

It is assumed that the allocations of first strike ICBM and SLBM RVs to missiles, air bases, and value are equal. The portion directed at missiles is  $x'(mM + nN)$ ; that directed at aircraft is  $y'(mM + nN)$ ; and that directed at value is  $(1 - x' - y')(mM + nN)$ . The portion that penetrates the boost phase is  $(pmM + qnN) \equiv R$ . The portions that arrive over missiles, air bases, and value are thus  $x'R$ ,  $y'R$ , and  $(1 - x' - y')R$ , respectively. The number of weapons that actually reach value targets is  $(1 - x' - y')R$  less the  $(1 - g - h)I$  interceptors assigned to them or

$$R' \equiv \max\{(1 - x' - y')R - (1 - x' - y')Rx', 0\}. \quad (7)$$

Figure 2 shows the successful RV strikes on value. For  $K$  small, or  $p \approx 1$ , those strikes decrease monotonically with  $I$ . For  $K > 0$  they decrease exponentially. For  $I = 2,000$   $R'$  falls to 0 by 2,000 SBIs, and RVs contribute nothing. Both sides have  $V \approx 2,000$  value targets of their own to protect and a like number of the other's to hold at risk. Thus, for large defenses, RVs contribute little to either objective. The number of penetrating RVs is not large enough to impact them.

Aircraft weapons are added to the RVs that arrived earlier to determine the total first strike on value,  $R_1'$ , which is shown in Fig. 3. The total strikes range somewhat irregularly from 4,500 to  $\approx 6,000$ . For small  $K$  a significant contribution comes from the RVs, but as the number of SBIs increase, the total strikes fall. For large  $K$  the survival probability varies as  $\epsilon \approx (1 - p)^m \approx 1 - mp$  and the first strike falls as  $1 - \epsilon \approx mp$ . Contributions from RVs fall, and that from aircraft also increases. By 4,000 SBIs the total strike falls to essentially that from aircraft in accordance with Fig. 2. For all  $I$  and  $K$  the first strikes remain large compared to  $V$ . Thus, the first strikes are robust, though they are mostly from aircraft.

#### V. RESTRIKES

The restrike is made up of surviving aircraft and missiles. The aircraft contribution is from both alert and nonalert,

defended aircraft. The missile contribution is only from those that ride out the attack, survive, and then launch.

#### A. Aircraft

Aircraft carry a significant component of the restrike. Thus, their prelaunch destruction or survival rate is pivotal, and they should be attacked accordingly. The nominal attack assumes that  $0.3 \cdot 5,100 = 1,530$  RVs would be directed at 50-100 bases, or 15-30 RVs per base. It would be difficult to defend against that number. But if only 15% penetrated, the number would be reduced to 2-4 per base, which might be addressed.

Figure 4 shows aircraft prelaunch survivability,  $\epsilon_b$ , as a function of I and K. For  $I = 0$ ,  $\epsilon_b$  is calculated as in Eq. (5) with the number of targets set equal to the  $T \approx 100$  main and dispersal bases available, which gives

$$\epsilon_b \approx (1 - p)^{X'mM/T} \cdot (1 - q)^{Y'nN/T}. \quad (8)$$

The first term is for the ICBM RVs aimed at aircraft bases; the second for SLBM RVs. For  $p \approx q$ ,  $\epsilon_b \approx (1 - p)^{X'R'/T}$ , as before in Eq. (5). The ICBM and SLBM attacks just compound.

For  $I > T$ ,  $\epsilon_b$  is calculated from Eq. (6), which gives

$$\epsilon_b \approx [\theta hI/Y'p_mM]^{0.9 \cdot p^{0.64}} \cdot [(1-\theta)hI/Y'q_nN]^{0.9 \cdot q^{0.64}} \quad (9)$$

where the two terms come from ICBM and SLBM RVs as before and  $\theta = 1/[1 + (q/p)^{0.64}]$  is the allocation of the interceptors between them that maximizes  $\epsilon_b$ . For large I the number of targets essentially cancels out of  $\epsilon_b$ .

$\epsilon_b$  increases monotonically with I at every K and with K for each I. For  $I \rightarrow 0$ , i.e. weak or nonpreferential layers,  $\epsilon_b \rightarrow 0$  for most K, although by  $K \approx 4,000$ ,  $\epsilon_b$  grows to about 0.15 even for  $I = 0$ . Figure 5 gives the aircraft contribution to the restrike, which is the sum of the  $\alpha \approx 30\%$  of the aircraft assumed to be on alert plus a fraction  $\epsilon_b$  of the nonalert aircraft. The total number of aircraft weapons in the restrike is thus

$$W = [\alpha + (1-\alpha)\epsilon_b]B. \quad (10)$$

W resembles  $\epsilon_b$  but is shifted up by  $\alpha B$  and rescaled by  $(1 - \alpha)B$ . For  $I = 1,000$  the sum rises to  $\approx 65\%$  of the aircraft by 2,000 SBIs.

Aircraft arrive long after the RVs. Thus, all of their weapons would be deposited on value, since there would be little else left to strike. Once airborne, they would have no other impediment to completing their strikes, providing there were enough penetrating RVs or onboard countermeasures to suppress or avoid the defenses.

If the attacker had B aircraft-borne weapons that struck from an alert rate of  $\alpha \approx 30\%$ , and the rest of his aircraft were destroyed, that would leave  $\alpha \cdot B$  weapons for the first strike. Ideally, the attacker would make  $\alpha \rightarrow 1$  to maximize his first strike. However, that could be detected and compensated for. The defender could disperse his aircraft to increase his alert rate, which could largely negate the benefit of striking first. Thus, the attacker's alert rate might be little greater than the nominal  $\alpha \approx 30\%$ .

Stability indices are sensitive to  $\alpha$ , since the contribution from aircraft is larger than that from RVs for moderate to strong defenses. For that reason results are sensitive to measures such as attacks on aircraft by close-in cruise missiles or SLBMs--particularly those on depressed trajectories, which could greatly reduce the aircraft warning time, effective alert rates, and hence survivability.

## B. Missiles

Restrike ICBM RVs must survive to contribute to the restrike. The probability of a missile riding out the first strike without midcourse defenses is as before

$$\epsilon_m \approx (1 - p)^{Y^m} \cdot (1 - q)^{Y^n N/M}. \quad (11)$$

That with defenses is

$$\epsilon_m \approx [\theta g I / x' p m M]^{0.9 \cdot p^{0.64}} \cdot [(1 - \theta) g I / x' q n N]^{0.9 \cdot q^{0.64}}. \quad (12)$$

Figure 6 shows the missiles' survival probability. For  $I > 0$  the curves are much as for aircraft survival; for  $I = 0$  the missile curve is somewhat higher because there are more missiles than air bases, which dilutes the penetrating RVs.

If the defender and attacker have the same number of missiles and RVs before the attack, the number of ICBMs the

defender could launch as a restrike is only  $\epsilon \cdot M$ . The attacker's boost-phase layer's performance would improve against smaller restrikes, so the restrike's penetration of the attacker's boost-phase defenses would only be

$$r \approx e^{-fK/\epsilon M} = (e^{-fK/M})^{1/\epsilon} = p^{1/\epsilon}, \quad (13)$$

which is shown in Fig. 7. For  $\epsilon$  small,  $r \ll p$ . For strong defenses,  $\epsilon \rightarrow 1$  and  $r \rightarrow p$ , which reduce the advantage for attacking first. For large  $K$  the top curve for 2,000 preferential interceptors is virtually the same as  $p$  of Fig. 1. For  $I = 0$  few restriking RVs penetrate, but for  $I > 0$  a monotonically increasing fraction would. By  $I = 1,000$  about 20% would; by 2,000 about 50% would.

The fraction of restriking ICBM RVs that would survive and penetrate the attacker's boost phase defense is  $\epsilon \cdot r$ , which is shown in Fig. 8. The long, flat tails in Fig. 7 lead to the relatively flat tails in  $R$  in Fig. 8. For  $I = 0$ , few RVs penetrate; for  $I = 2,000$  about 40% survive and penetrate by  $K = 2,000$ ; by  $K = 4,000$  only about 15% or 400 RVs do.

For SLBMs,  $\epsilon \approx 1$ , which offsets their disadvantage in pre-launch survivability. Thus, the total RVs surviving and penetrating the boost phase defenses is

$$R = mMer + nNp, \quad (14)$$

which resembles the first strike RV penetration of Fig. 2. It is primarily composed of SLBM RVs. That curve must still be clipped by the attacker's preferential defenses. That produces the curves shown on Fig. 9, which are well below the first strike missile curves in Fig. 3. For moderate to large defenses with  $I > 0$  neither the ICBM nor SLBM RVs contribute significantly to the restrike.

### C. Total Restrike

The total restrike  $R_2$ , is the sum of the aircraft and missile contributions corrected for the defenses encountered. It is shown in Fig. 10. The curve for  $I = 0$  drops slightly but is relatively flat overall. The other curves rise sharply to the  $\approx 4,500$  weapons contributed by the aircraft and hold there. For

500 preferential interceptors the rise is completed by 4,000 SBIs; for 1,000 by 3,000 SBIs; and for 2,000 by  $\approx 2,000$  SBIs. The total number of interceptors needed to reach the asymptote is about constant. Adding midcourse interceptors simply makes it possible to make that rise with fewer SBIs.

It is interesting that for large  $K$  the restrikes converge to two trajectories: that for  $I \approx 0$  and those for  $I > 0$ , for which air base defense is possible. For them the asymptote is about equal to the number of aircraft-borne weapons in the first strike from Fig. 3, so the first and second strikes are asymptotically equal.

It is clear that without a preferential layer the defender's missiles would be drawn down strongly and nonalert aircraft eliminated altogether. Thus, all of the major components of his retaliatory strike would be reduced without compensation, which would degrade crisis stability. With preferential defenses, however, it is possible for more aircraft to survive, penetrate, and perform their deterrent function. Thus there is a shift from RV- to aircraft-based retaliation, which occurs at quite modest numbers of SBIs.

#### D. Nonalert Aircraft Strikes

The figures above make it possible to resolve the survivability of the attacker's nonalert aircraft, which carry about half of his weapons. Of the weapons treated here, the nonalert aircraft are accessible only to missiles. It would be desirable for the side attacked to respond by destroying those nonalert attack aircraft before they could take off, but doing so would require that he be able to deliver enough RVs to do so. It is clear from the above that would be difficult for strong defenses.

Figure 11 shows the nonalert aircraft survival probabilities as functions of  $K$  and  $I$  when attacked by for of the missile restrike of Fig. 9 under the assumption that the attacker provides adaptive preferential defenses for them with half of his preferential interceptors.



The attacker's nonalert survival probabilities are much higher than the defender's probabilities of Fig. 5 because the restrikes are much smaller. For  $K > 0$  most of his aircraft survive even for small  $I$ . For large  $I$  over 90% survive. These values give the attacker a significant advantage, particularly at  $I \approx 0$ , where most of his nonalert aircraft would survive while most of the defender's nonalert aircraft would be destroyed. In practice most of the attacker's nonalert aircraft survive to contribute to his first strike.

## VI. COSTS AND CRISIS STABILITY INDICES

The costs for the first striker are those for his imperfect limiting of damage to his value and for his imperfect strike on the other's value.<sup>19</sup> These two costs can be expressed in terms of the first,  $R_1$ , and second,  $R_2$ , strikes on value discussed above. The total costs are weighted averages of them. For exponential damage functions, the costs for striking first and second are<sup>20</sup>

$$C_1 = 1 - e^{-R_2/V} + L \cdot e^{-R_1/V}, \quad (15)$$

$$C_2 = 1 - e^{-R_1/V} + L \cdot e^{-R_2/V}. \quad (16)$$

where  $V$  is the number of targets held at risk.  $L$  is the relative weighting of value strikes and damage limiting.  $L = 0.3$  is used below; the results are not sensitive to the precise value.<sup>21</sup>

Figure 12 shows the costs of first strikes for the  $R_1$  and  $R_2$  above. At  $K = 0$  the curve for  $I = 0$  is at 0.75; the other curves are slightly lower. The spread is a rough measure of the error in Eq. (6), which was meant to be accurate at large  $I$  and  $K$ . The curve for  $I = 0$  falls as  $K$  increases, indicating reduced stability, although it rises again for  $K > 2,500$ . The others rise almost monotonically to a limiting value of  $\approx 0.93$ . Those with more preferential interceptors reach that value sooner. Once again the curves converge to two trajectories. That for  $I \approx 0$  falls to  $\approx 0.6$ ; the rest converge to  $\approx 0.93$ . For all  $I > 0$  the costs to the attacker for striking first increase to levels significantly greater than those without defenses.

Figure 13 shows the costs of second strikes. That for  $I = 0$  is about flat; those for 1,000 and 2,000 SBIs fall monotonically to  $\approx 0.93$ . That for 500 does, too, above 500 SBIs, and its variation below that is noise. That the costs for waiting rather than striking first fall monotonically with increasing defenses indicates increasing stability, as does the fact that they fall to asymptotic limits that are about the limiting first strike costs of Fig. 12.

These two costs can be combined into a stability index. A heuristic derivation of the index is possible,<sup>22</sup> but it is simply observed here that increasing the cost for striking first or decreasing the cost for striking second would appear intuitively to be stabilizing, so a logical and useful index of stability is their ratio  $C_1/C_2$ . Figure 14 shows  $C_1/C_2$  as functions of the number of midcourse interceptors and SBIs. The index for  $I = 0$  falls to  $\approx 0.55$  at 2,500 SBIs; the others rise essentially monotonically. Each reaches a value of  $\approx 1$ , neutral stability. Those with the most preferential interceptors just reach that level first. These trends indicate that defenses with comparable numbers of boost-phase and midcourse defenses could be stabilizing throughout.

## VII. SENSITIVITIES

The above calculations used nominal allocations of attacks and defenses rather than reoptimizing them for each combination of overall defenses. This section discusses the sensitivity to results to those allocations, which is modest. The sensitivity studies are performed for  $K = 2,000$  SBIs and  $I = 1,000$ , which according to the figures above should be the region in which the indices should be the most sensitive to variations in defense allocations.

### A. Attack Allocation

Figure 15 shows the restrike  $R_2$  as a function of  $g$ , the fraction of the preferential defenders that are allocated to the defense of missiles, for allocations of  $x = 0.3$  and  $0.5$  of the

attacking RVs to missiles. As above, 30% of the RVs are allocated to the value targets; thus, 50 and 70%, respectively, of the RVs are allocated to aircraft bases for the two cases.

The top curve is for  $x = 0.5$ . It has a maximum of about 4,500 weapons for  $g$  small. There, the attack falls primarily on the missiles, which are lightly defended, and most of the strongly defended airbases survive, which gives the large value of  $R_2$  shown.  $R_2$  falls off slowly as the fraction of defenses allocated to missiles increases because the fraction of the defense allocated to the airbases decreases and more aircraft are destroyed. More missiles survive, but few penetrate, so the total restrike decreases to about 3,000 weapons by  $g = 0.6$ .

The curve for  $x = 0.3$  is only about  $R_2 \approx 3,700$  weapons at  $G = 0.2$ , but it falls somewhat more slowly, so that it is only slightly lower than that for  $x = 0.5$  by  $g = 0.6$ . For the adaptive defenses assumed here, once the attacker has made his allocation the defender can observe it and make his allocation to maximize  $R_2$ . The attacker must bear that in mind in choosing the  $x$  that optimizes  $R_1$ , as discussed below. The simple result, however, is that the attacker minimizes the restrike by concentrating on the airbases, and the attackee maximizes his restrike by defending them most strongly. The restrikes are not, however, particularly sensitive to values near the  $G = x = 0.3$  used in earlier sections.

The basis for the variation seen in Fig. 15 is shown further in Fig. 16, which gives the attackee aircraft survival probability as a function of  $g$ . Both fall monotonically with  $g$ . The upper curve falls from 1 to 0.45 as  $g$  increases from 0.2 to 0.6; the lower curve for  $x = 0.3$  falls from 0.75 to 0.3. That produces the incentive for the attackee to allocate more defenses to the more penetrating aircraft.

#### B. Nonalert Aircraft

Given the large number of penetrating weapons carried on aircraft in START conditions, the defender would like to suppress them. The difficulty is that suppressing airbases with adaptive

defenses would take a large number of penetrating RVs, while for typical conditions few restrike RVs penetrate. The defender decides the percentage,  $Y$ , of his restriking RVs to allocate to suppression of the nonalert aircraft and what percentage to allocate to striking value. The attacker, after observing that allocation, then decides what percentage,  $H$ , of his preferential interceptors to devote to defending the nonalert aircraft and what percentage to defending value.

Figure 17 shows the size of the first and second strikes as functions of the fraction of the attacker's preferential defenses allocated to defending his nonalert aircraft,  $H$ , for attackee allocations to their suppression  $Y$ . The top two curves are the first strikes; the bottom two curves are the second strikes. For each, the upper curve is for  $Y = 0.3$  and the lower for  $0.7$ . The attacker would like to maximize  $R_1$ . For  $Y = 0.3$  that would mean operating at  $H > 0.3$ , where most of his nonalert aircraft would be defended and contribute directly to  $R_1$ . For  $Y = 0.7$ , i.e. lesser attacks on the attacker's nonalert aircraft, he would need to operate at  $H > 0.7$  to meet the stronger attacks on his nonalert aircraft.

Note from the bottom curves that if the attacker operated far above those break points, the restrike  $R_2$  would rise with no compensating increase in  $R_1$ . Thus,  $H \approx Y$  is a reasonable joint allocation of restrike assets and defenses to nonalert aircraft.

### C. Costs

Figure 18 shows the corresponding first and second strike costs. The top two curves are for  $C_2$  for  $Y = 0.3$  and  $0.7$ , and the bottom two curves are for  $C_1$ . The  $C_2$  curve for  $Y = 0.3$  has a maximum at  $H \approx 0.3$ . The attacker would want to operate there to maximize the attackee's cost of striking second. Interestingly, from the bottom curve that choice would also minimize the cost of striking first. For  $Y = 0.7$  the maximum in  $C_2$  and the minimum in  $C_1$  is near  $H = 0.7$ . More interesting is that the resulting maxima and minima are about the same for either choice of  $Y$ .

The resulting crisis stability indices are shown in Fig. 19. At the left, the top curve is for  $Y = 0.7$ . It falls to a minimum of  $\approx 0.88$  at  $0.7$ . The curve for  $Y = 0.3$  has a minimum at  $H \approx 0.3$ , also  $\approx 0.88$ . Thus, wide variations in the attack and defense allocations change detailed strikes but do not alter the value of the overall crisis stability index. From the arguments of the previous sections, however, it is clear that the motivations of the attacker and attackee operate to produce allocations that minimize the overall crisis stability index for the given defenses. However, the values of  $\approx 0.9$  for these conditions appear acceptable. From Fig. 12 it would appear that those sensitivities would be further reduced for higher levels of defenses.

#### VIII. SUMMARY AND CONCLUSIONS

This note has derived a simple, approximate model for crisis stability that appears to contain most of the features needed to understand the variation of stability indices with defenses. In it ICBMs and SLBMs are attenuated exponentially. Singlets are not attenuated but do not matter at START levels. Midcourse defenses are preferential and adaptive. For modest, symmetrical defenses, most of the first and second strikes are carried by aircraft. If attack aircraft cannot be defended, restrikes can be larger than first strikes. If they can be, first strikes can asymptotically be as large as restrikes, and stability indices tend toward unity.

Under either assumption, first and second strikes are dominated by missiles in the absence of defenses, but transition to aircraft at modest levels of defense. Significant defenses protect some retaliatory missiles, but not enough to retaliate strongly. The reduced ICBM restrikes penetrate poorly; even SLBMs are ultimately suppressed. The burden of restrike thus shifts to aircraft. That makes discussion of factors that might reduce their prelaunch survivability important. For large defenses few missiles penetrate and stability is determined by the aircraft strikes. For equal forces the first and second

strikes from aircraft are about equal, so the stability indices tend rapidly towards unity.

This note does not address the ultimate goals of strategic defenses; it only treats the transition from deterrence by missiles to deterrence by aircraft. It indicates, however, that once effective defenses against missiles were deployed, the missiles would become vestigial and could be reduced or eliminated without reducing stability. After that was done the aircraft could be significantly reduced as well without significant loss of stability.

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Fig. 1 Missile penetration

$\alpha=0.3, m=10, M=270, B=4500, V=2000$

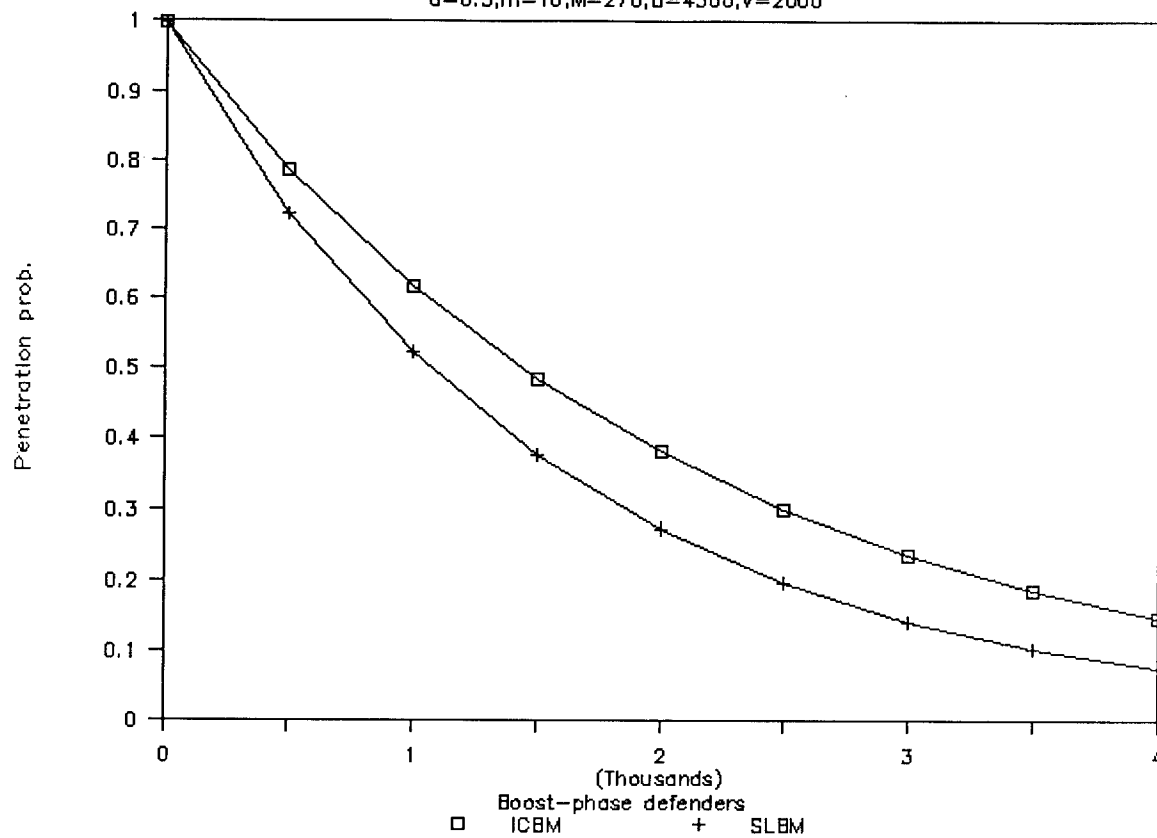


Fig. 2 Missile first strike on value

$\alpha=.3, m=10, M=270, n=6, N=400, B=4500, V=2000$

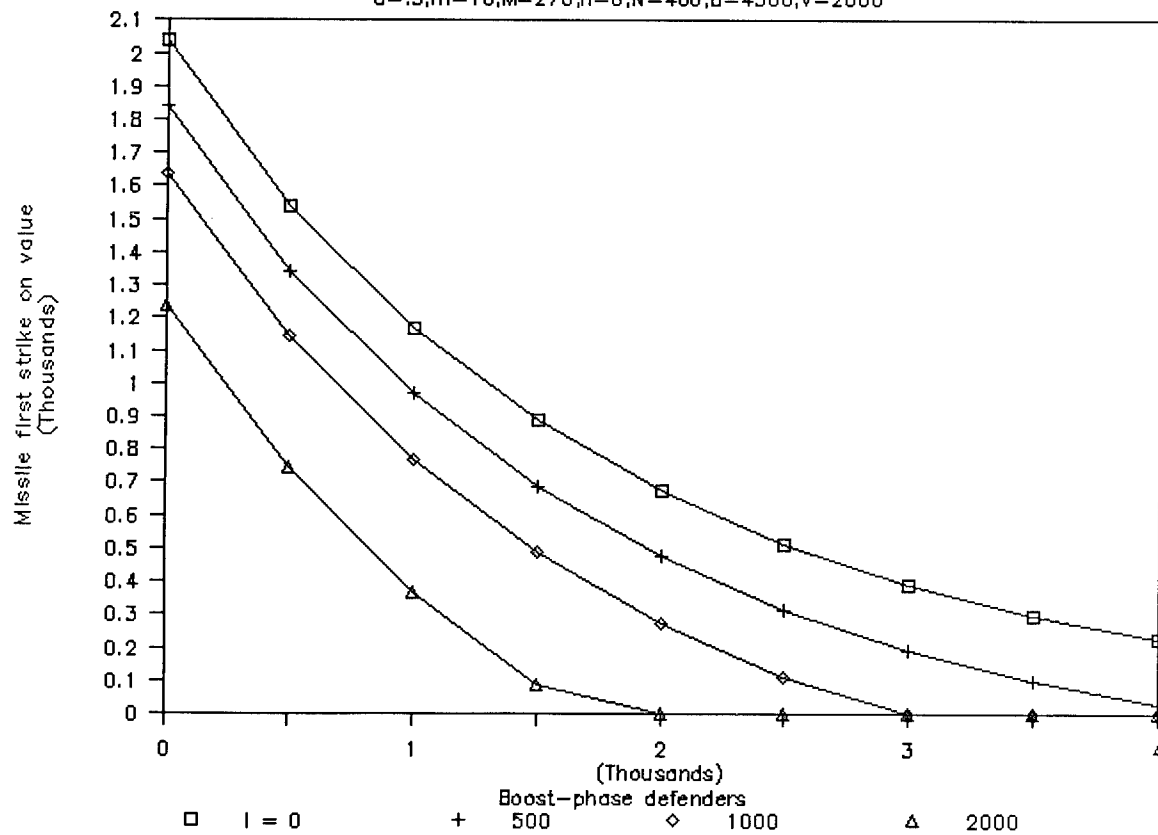


Fig. 3 First strike on value

$\alpha=.3, m=10, M=270, n=6, N=400, B=4500, V=2000$

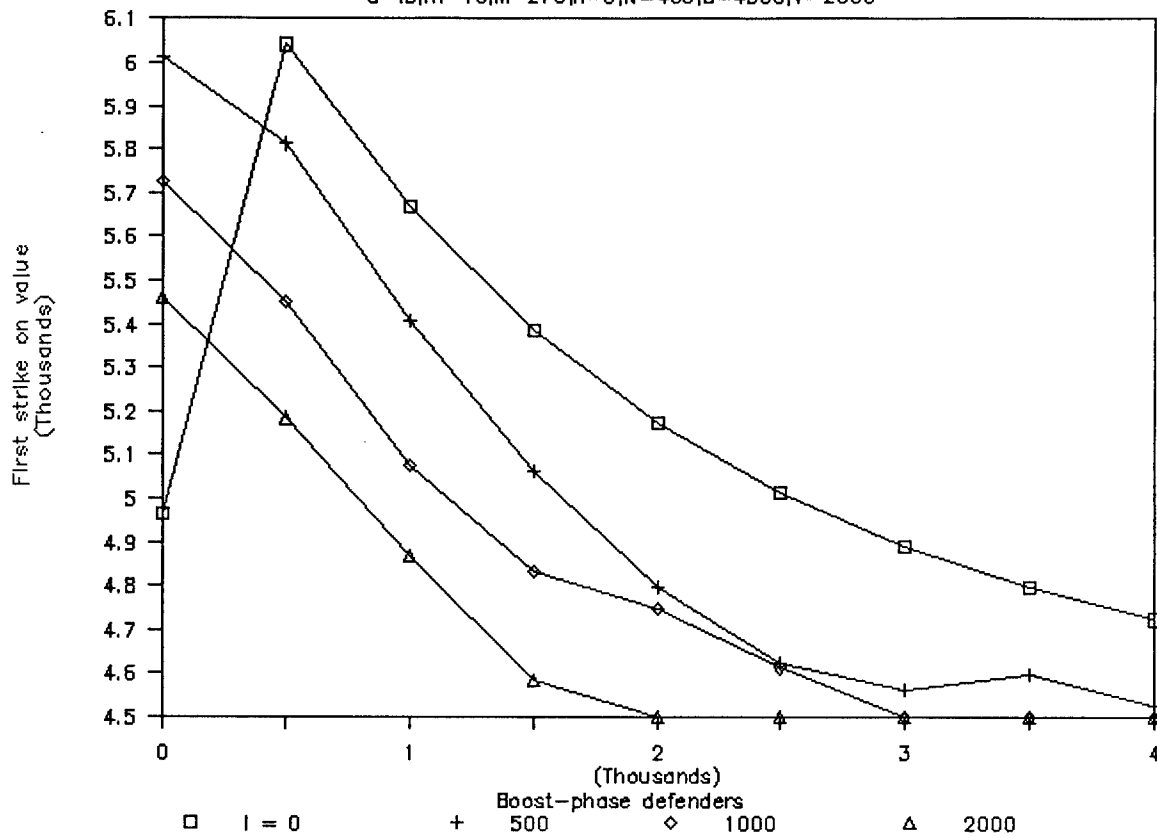


Fig. 4 Aircraft survival probability

$\alpha=.3, m=10, M=270, n=6, N=400, B=4500, V=2000$

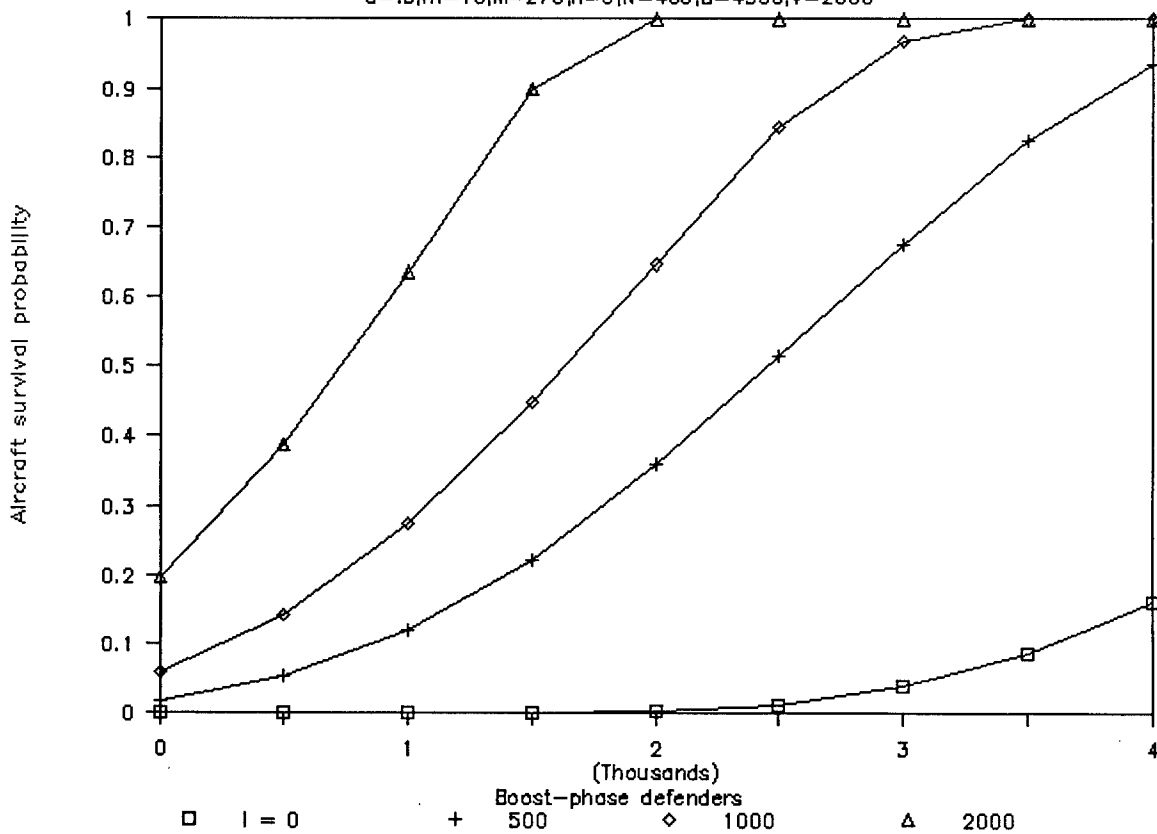


Fig. 5 Aircraft restrike on value

$\alpha=0.3, m=10, M=270, B=4500, V=2000$

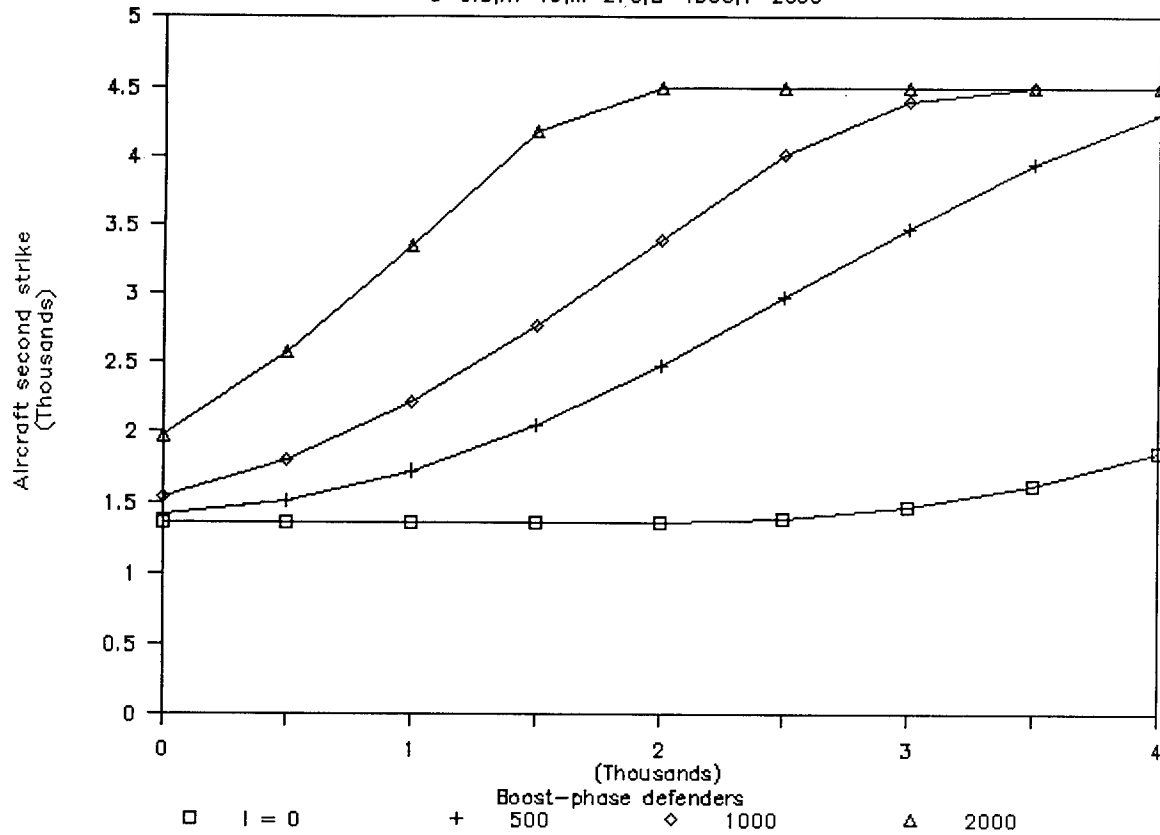


Fig. 6 ICBM survival probability

$\alpha=0.3, m=10, M=270, B=4500, V=2000$

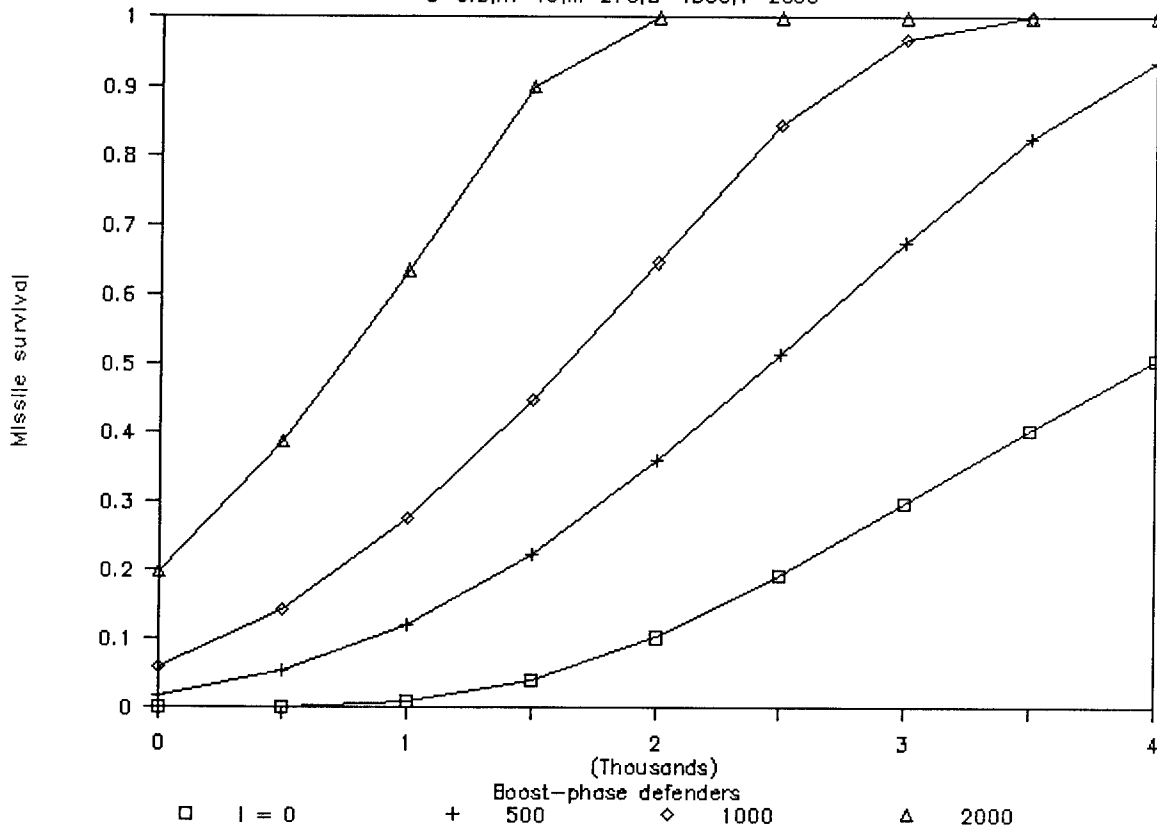


Fig. 7 Restrike ICBM penetration

$\alpha=0.3, m=10, M=270, B=4500, V=2000$

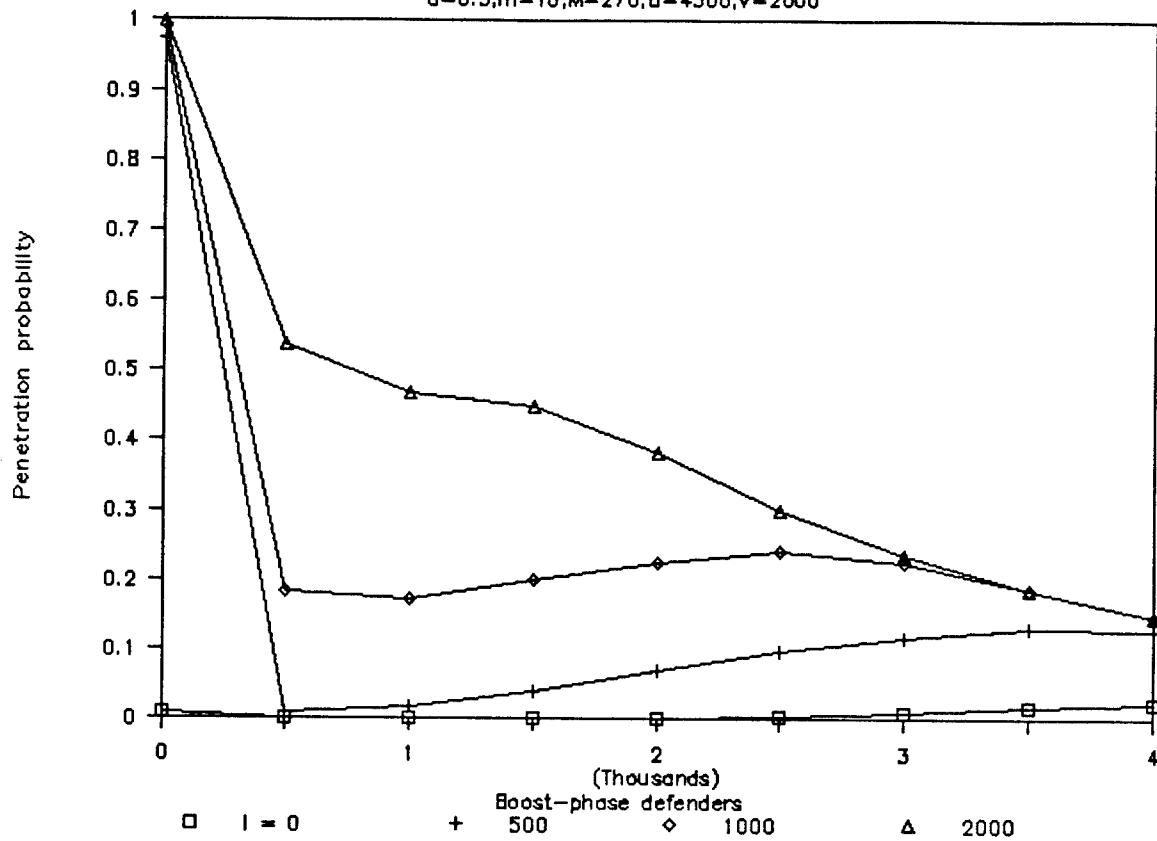


Fig. 8 Restrike ICBM survive & penetrate

$\alpha=0.3, m=10, M=270, B=4500, V=2000$

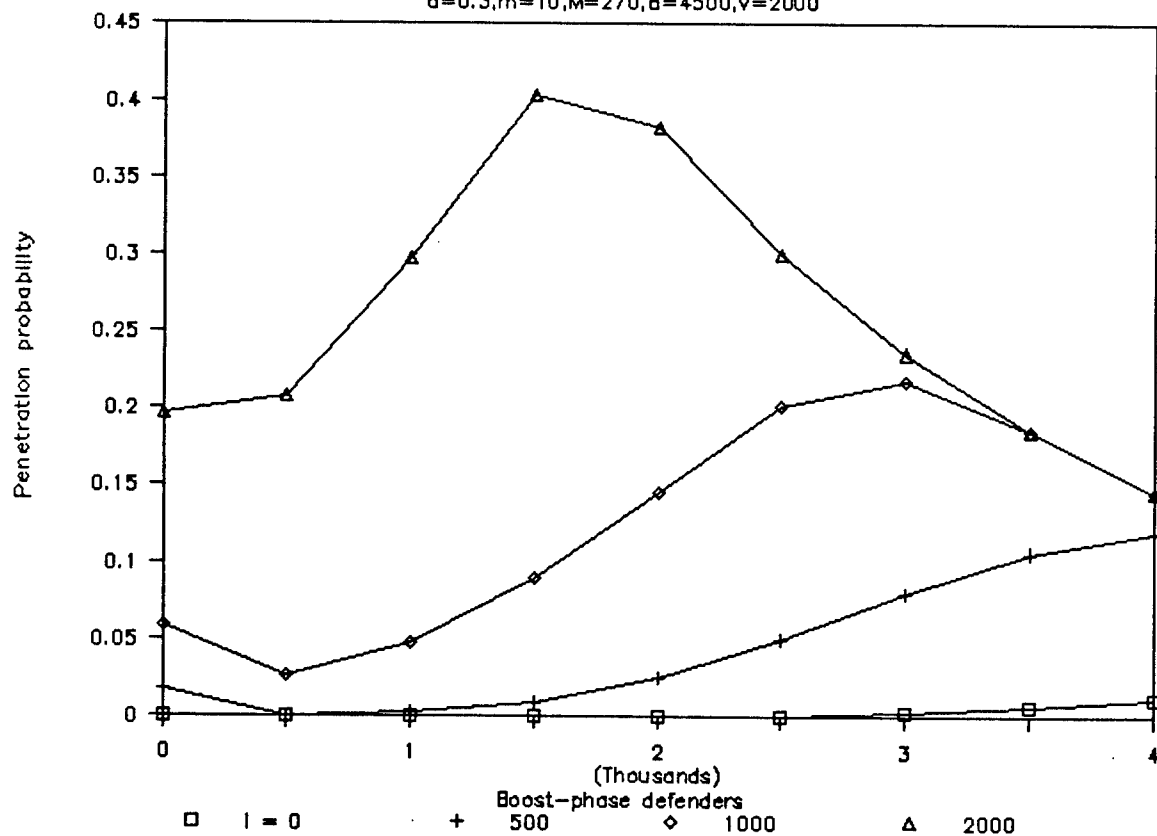


Fig. 9 Missile restrike on value

$\alpha=0.3, m=10, M=270, B=4500, V=2000$

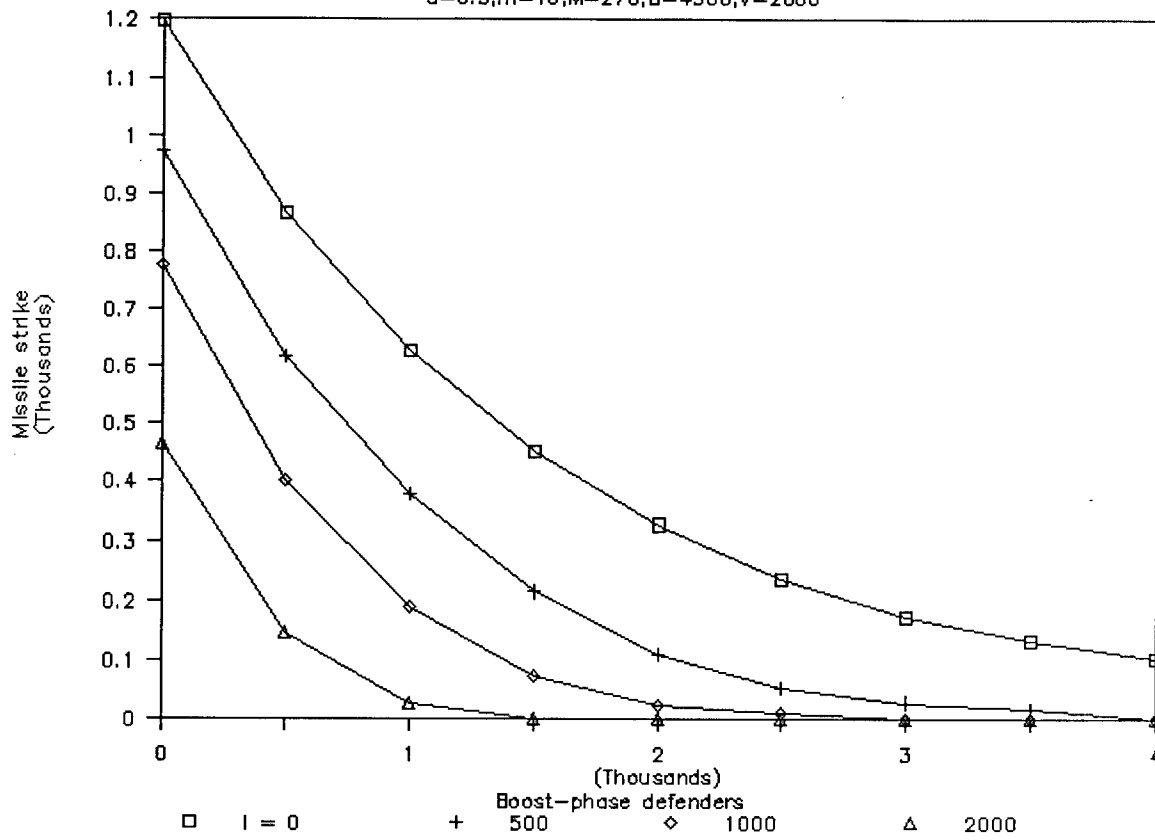


Fig. 10 Total restrike on value

$\alpha=0.3, m=10, M=270, B=4500, V=2000$

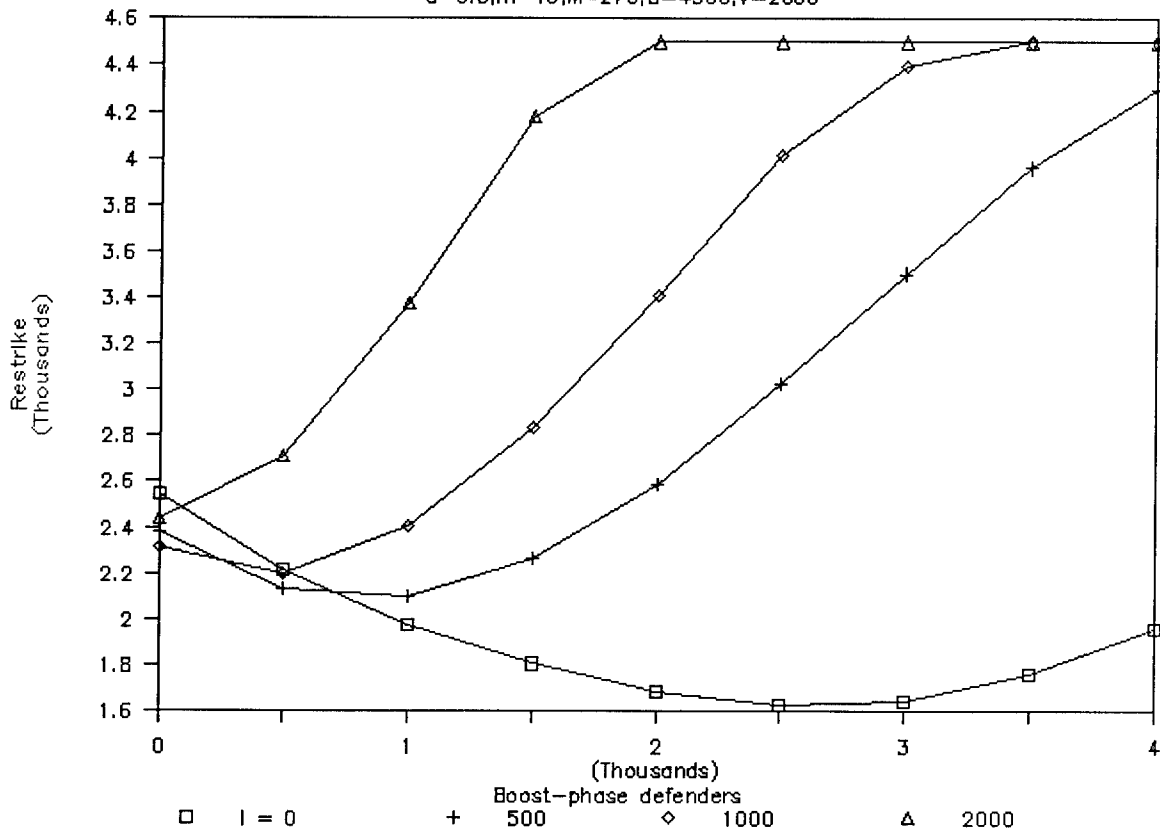


Fig. 11 Nonalert attack A/C survival

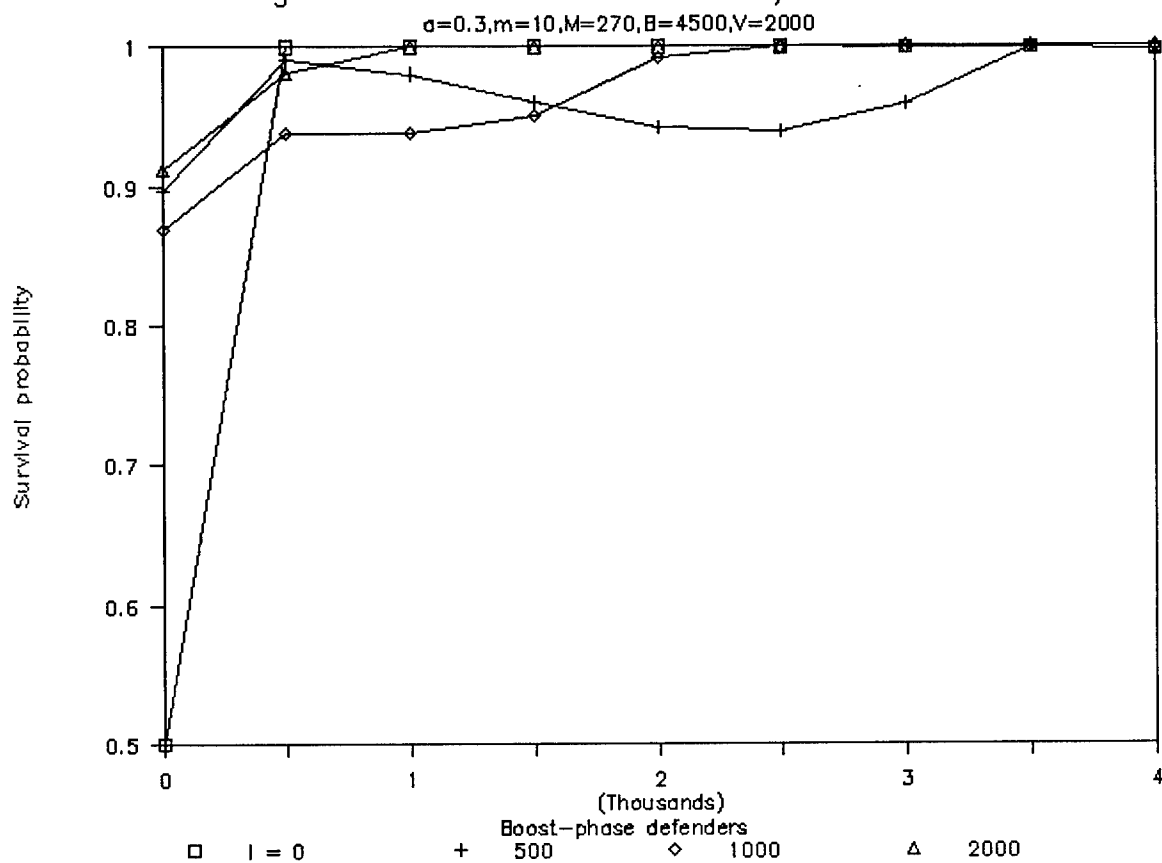


Fig. 12 First strike cost

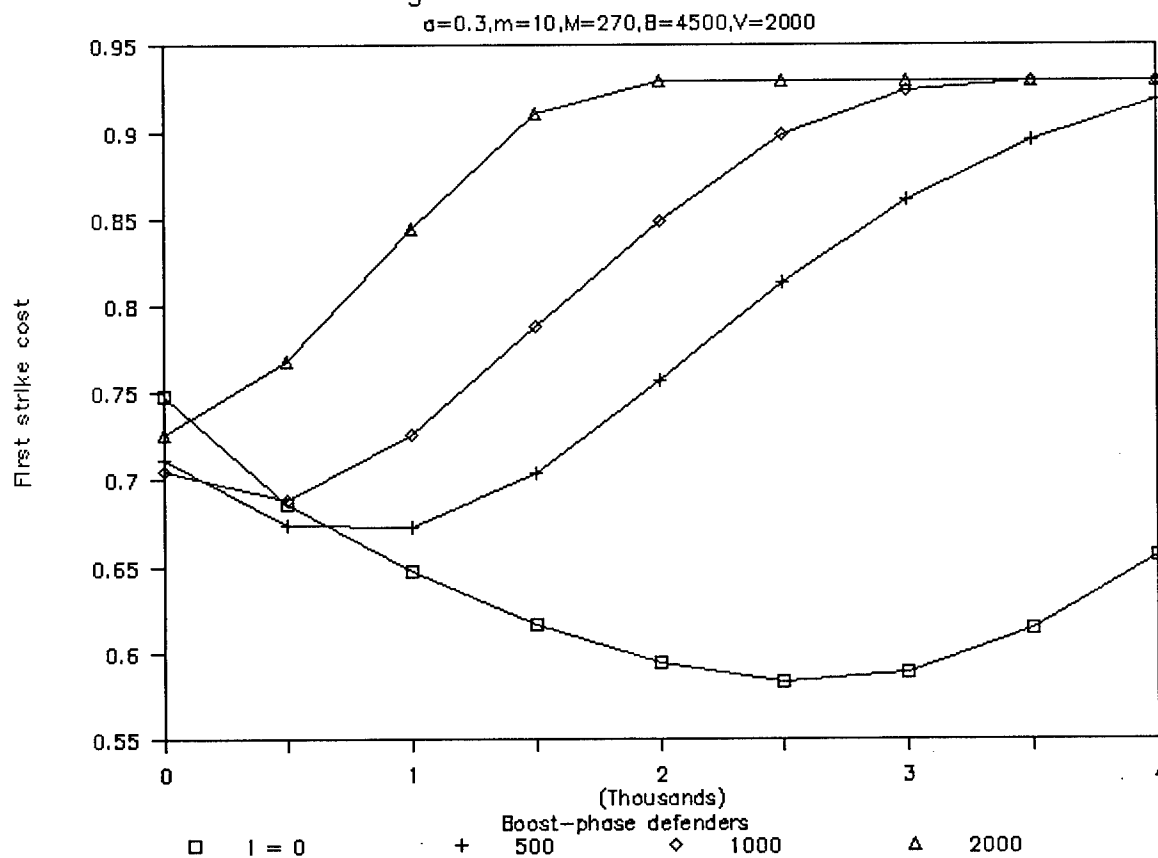


Fig. 13 Restrike cost

$\alpha=0.3, m=10, M=270, B=4500, V=2000$

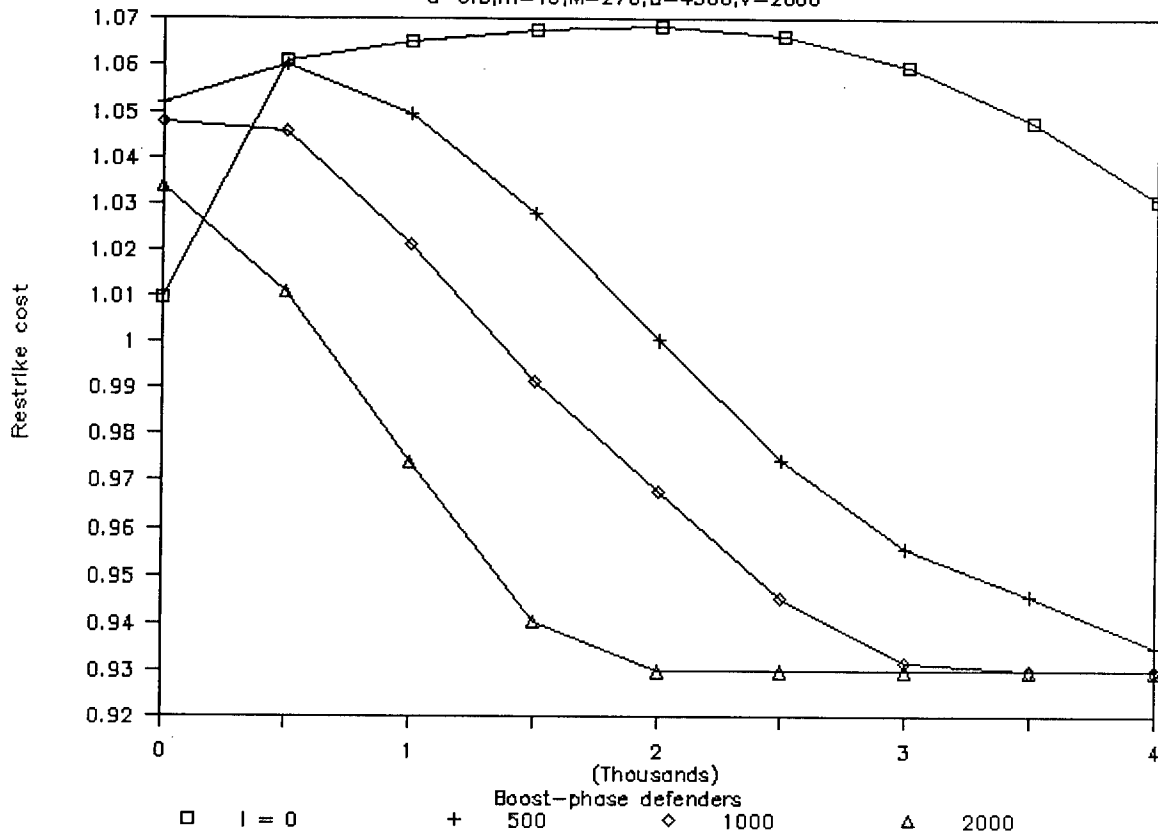


Fig. 14 Crisis stability index

$\alpha=0.3, m=10, M=270, B=400, V=2000$

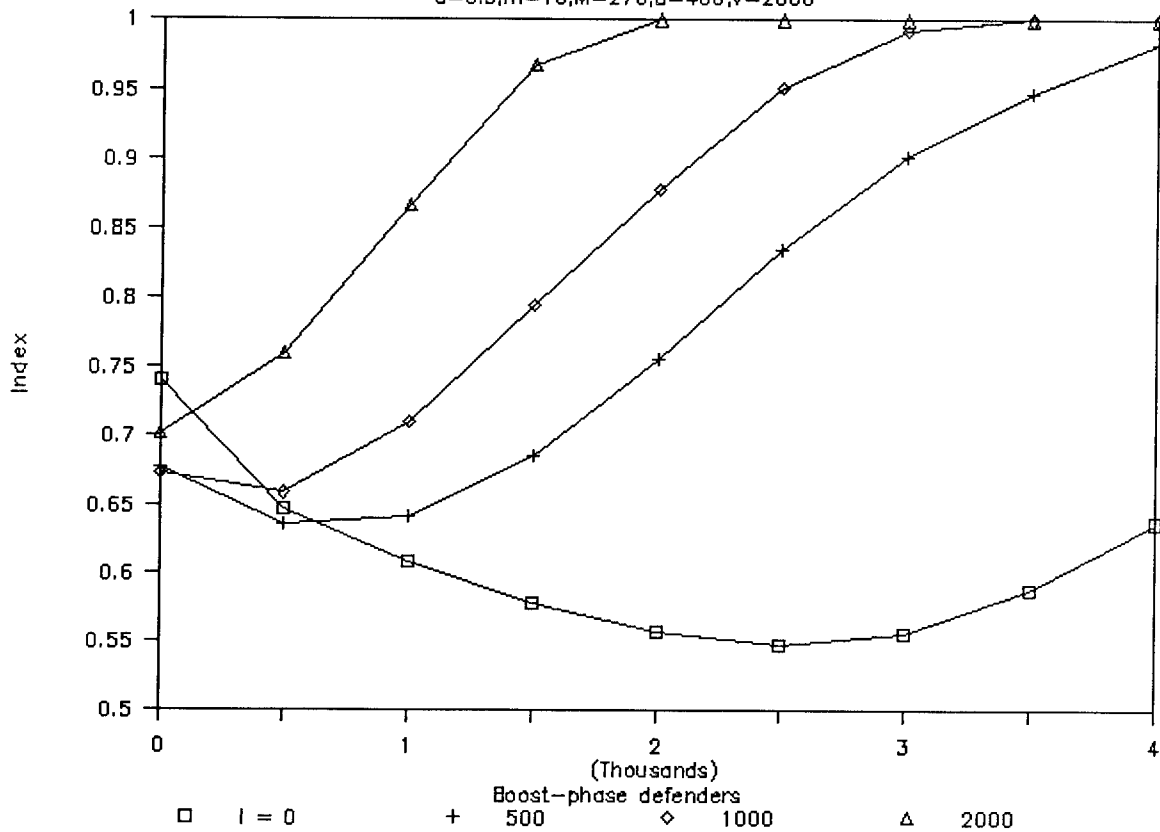


Fig. 15 Restrike sensitivity to attack

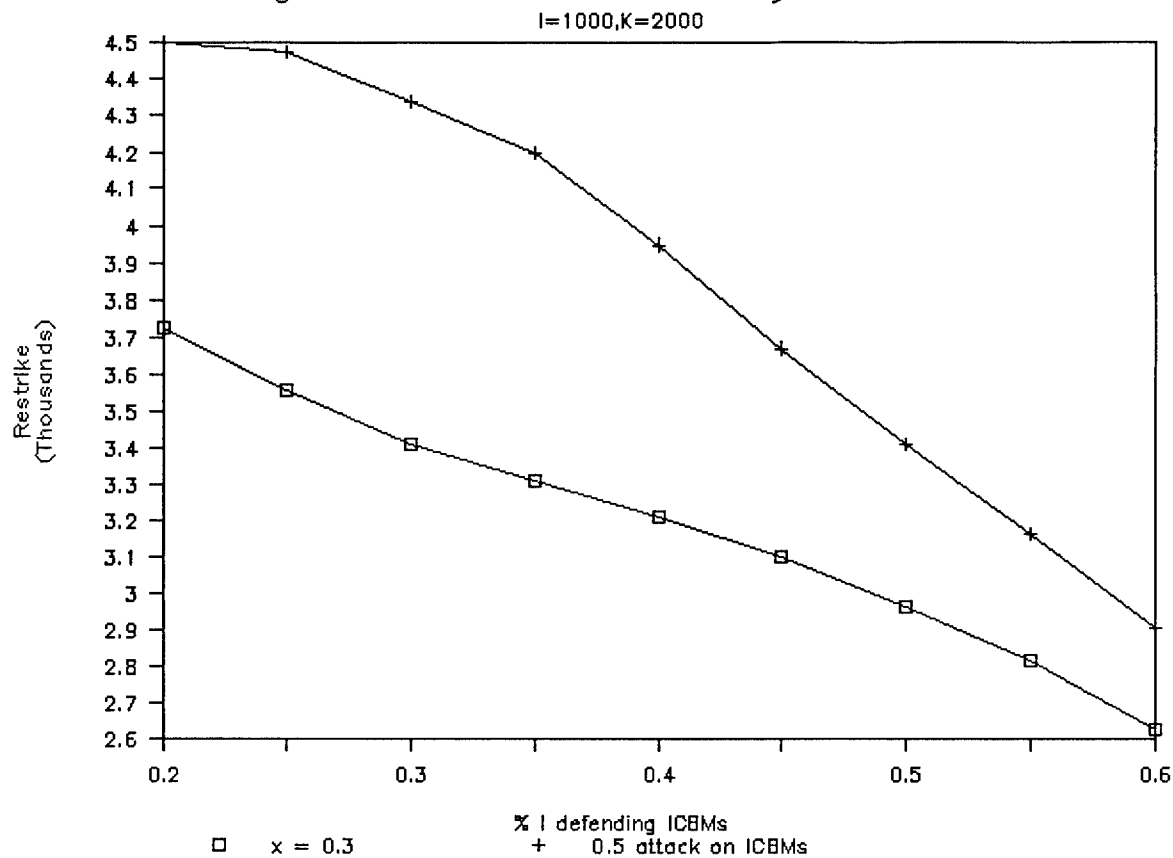


Fig. 16 A/C survival sensitivity

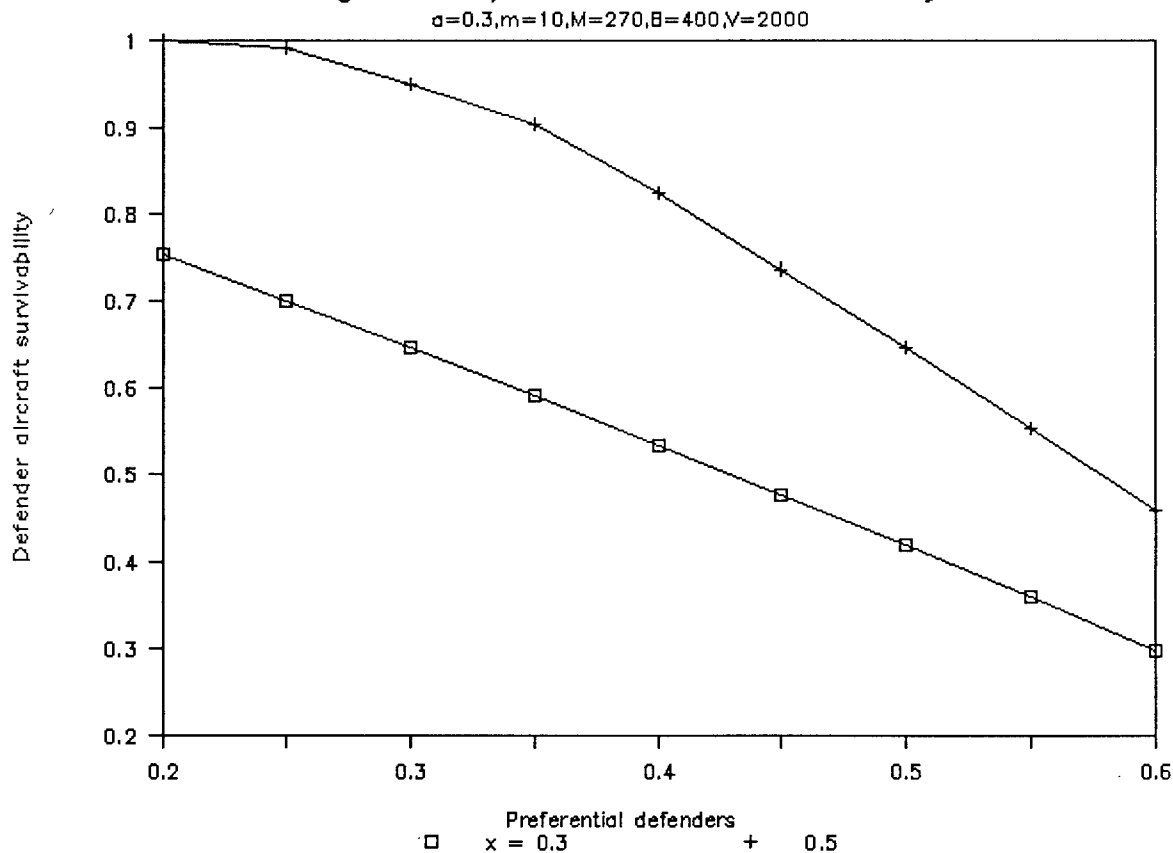




Fig. 17 Strike sensitivity nonalert AC

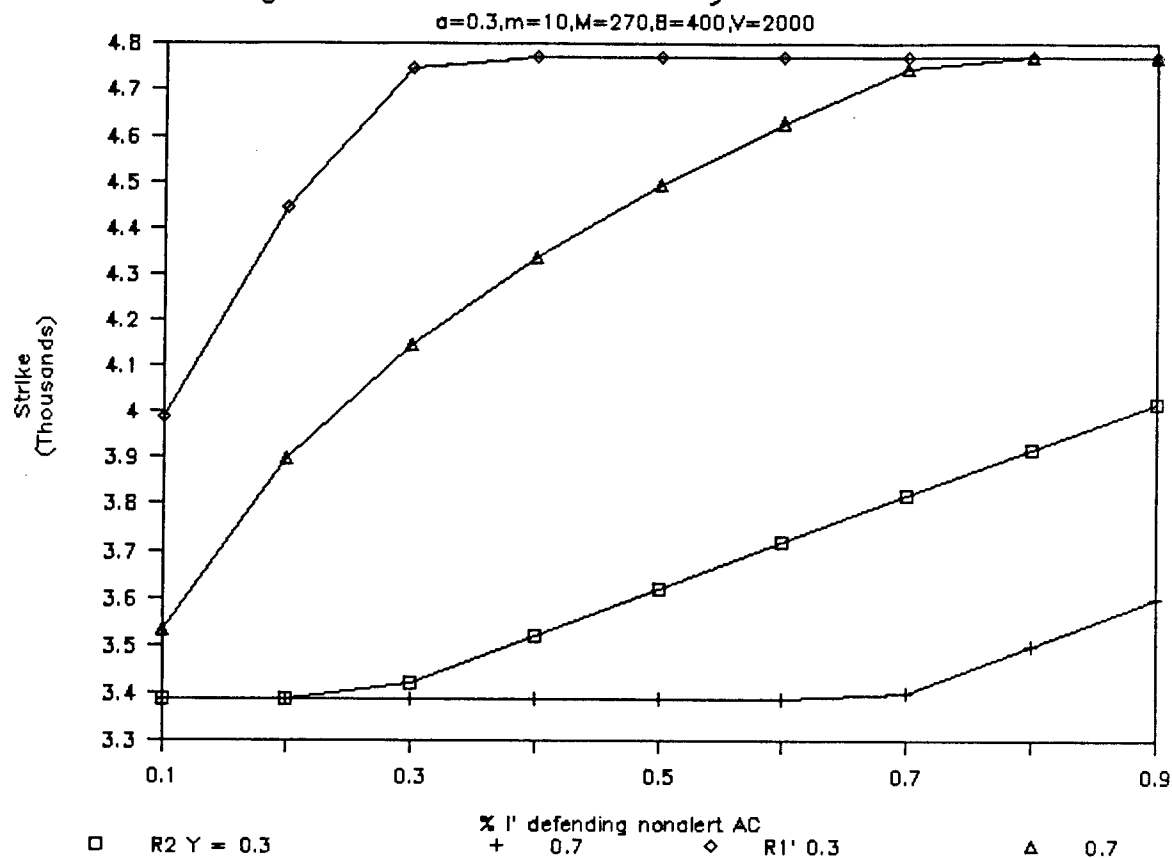


Fig. 18 Cost sensitivity to nonalert AC

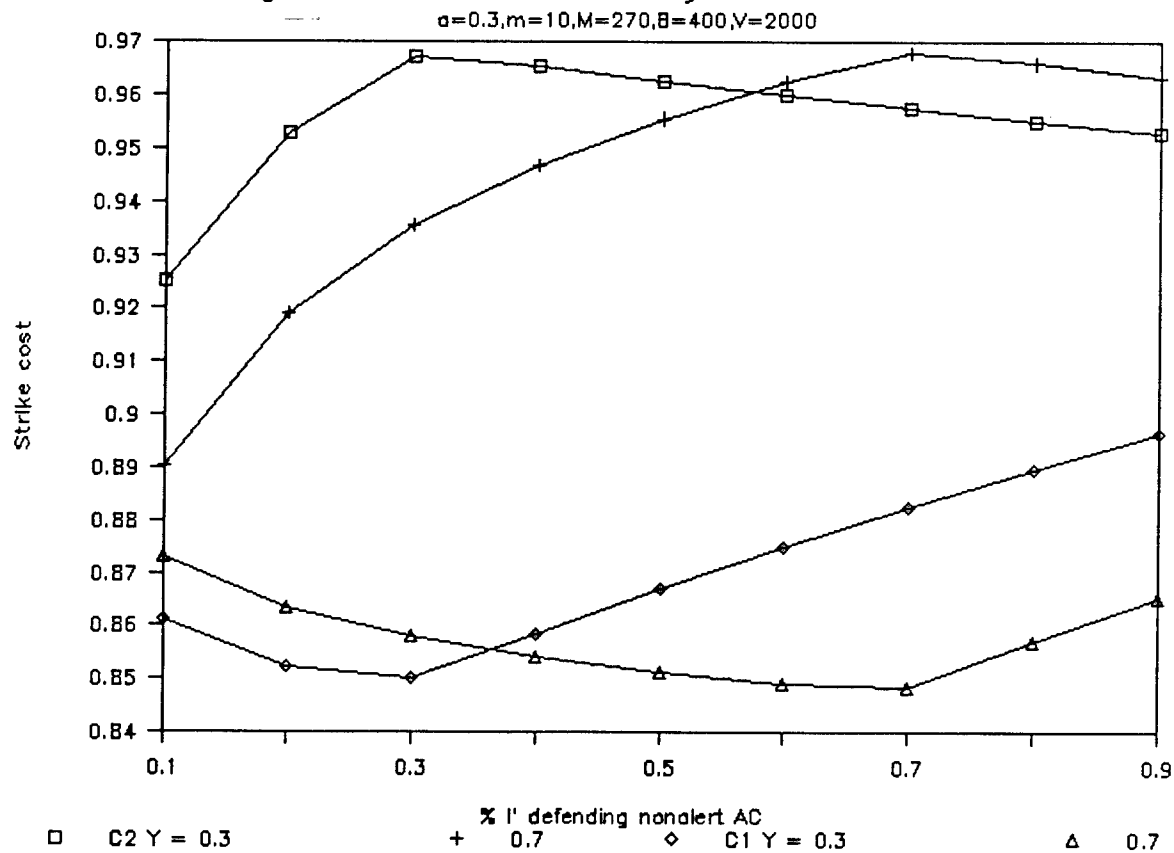
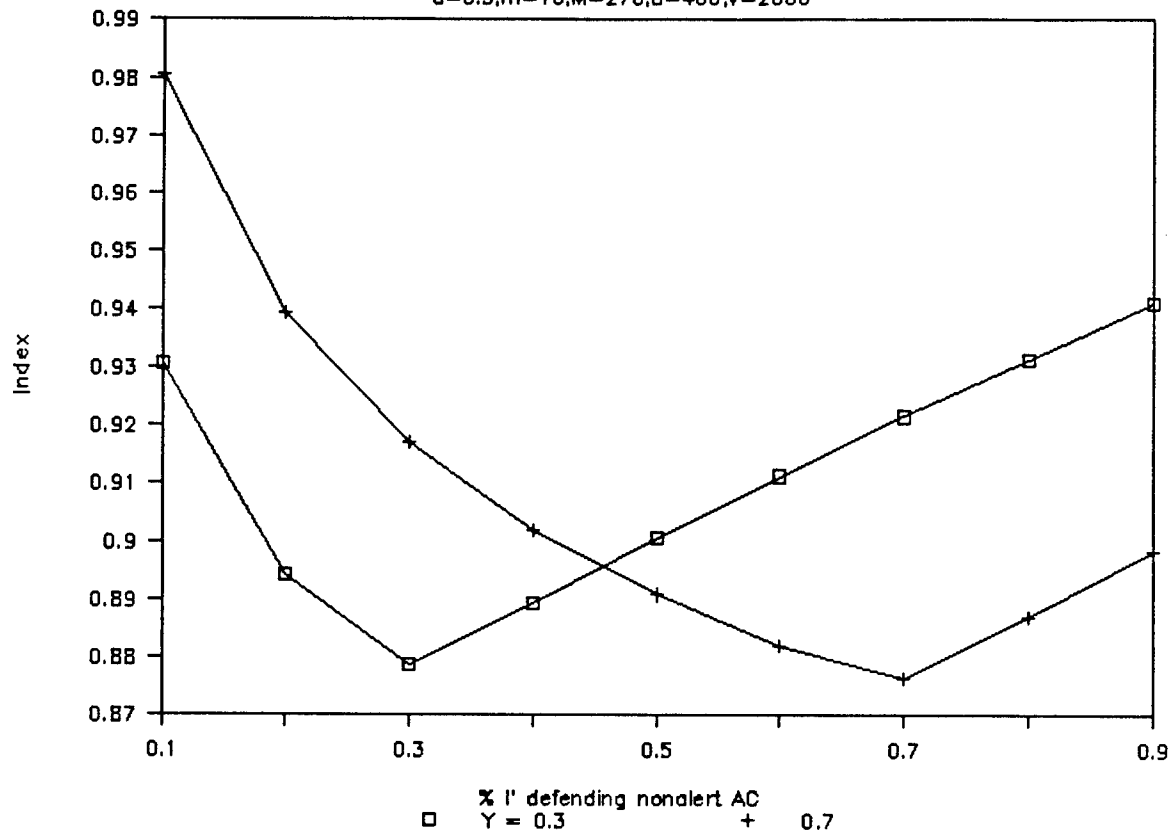


Fig. 19 Sensitiv index to nonalert A/C

$\alpha=0.3, m=10, M=270, B=400, Y=2000$



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